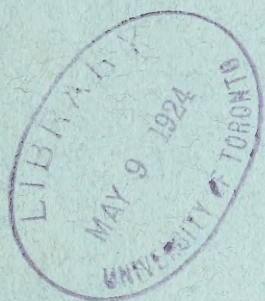


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BULLETIN  
OF  
The Terrestrial Electric  
Observatory

OF  
FERNANDO SANFORD  
Palo Alto, California



VOLUME I

Summary of Observations for the Period  
May, 1920-August, 1923

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## ELECTRIC INDUCTION OF THE SUN UPON THE EARTH

The investigation reported in the following pages had its origin in the belief that the phenomena of static electricity require for their explanation the existence of a very great negative charge upon the earth.\* The existence of such a charge seems necessary also for explaining the atmospheric potential gradient as well as the magnetic field of the earth.

Since the sun is magnetized in the same direction as the earth and rotates in the same direction upon its axis, it would seem that if the magnetic field of the earth is produced by the rotation of its negative charge, the sun, which has a magnetic field about fifty times as strong as that of the earth, must have a much greater negative charge. This, together with the fact that enormous negative charges have been shown to persist for months in the neighborhood of sun spots, while all attempts to observe the Stark effect around the borders of the areas known to be charged have failed, seemed to the writer to indicate that the sun is charged to a high enough potential to produce measurable induced charges upon the earth.

Such induced charges should be indicated by a permanent difference in the density of the earth's charge on its day and night sides. Since the earth is in constant rotation, such a difference in electrical density could be maintained only by electric currents flowing over or through the earth between its day and night sides.†

Although the earth has regularly been taken as the zero of electrical potential in electrostatic measurements, it has long been known that at any given time all parts of the earth are not at the same potential. This is shown by the fact that if any two distant points in the earth's surface,

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\* See *A Physical Theory of Electrification*, Stanford University Publications, 1911.

† Since the work described in the following pages was completed, I have found that such an inductive action of the sun as is here suggested has been proposed by various scientific writers in the past,—notably by Osborn Reynolds, in 1871 (*Mem. Lit. & Phil. Soc. Manchester*, Series III, Vol. V, pp. 44-56 and 202-209); by Werner Siemens (*Sitzungsberichte Berl. Akad.*, 1883, I, 625); and by Huggins in his *Bakerian Lecture on the Corona of the Sun*, in 1885 (*Proc. Roy. Soc.*, 39, p. 129). In a foot-note to this lecture, Huggins says:

"The sun being a charged conductor separated from the earth, also a conductor, by an insulating vacuum, would affect the distribution of the earth's electricity by its power of statical induction. As the earth rotates, currents would be set up about it to effect the redistribution of electricity required to satisfy the inducing influence of the sun. May we not find in these earth-currents an explanation of some of the phenomena of the earth's magnetism?"

either on land or on the sea, be connected by a metallic conductor a current is always found to be flowing in the conductor. Since a potential difference is a pre-requisite of a continuous current in a conductor, it would seem that *no* two places on the earth remain at the same electrical potential.

The currents which are known to flow continuously in the earth have, in general, a fairly permanent direction from day to day at any particular place, and their measured potential gradient is sufficient, if maintained around the earth, to indicate a potential difference of some thousands of volts between opposite points on the earth. Such observations as have been made upon them up to the present time indicate that, in general, positive currents are flowing from the night side of the earth toward the day side, or, in other words, that the free electrons in the earth are continually flowing from its day side to its night side. This indicates that if the earth were at rest its day side would be permanently electropositive to its night side. Such a condition can be maintained in a conductor only by induction from another charged body.

Since the earth-currents flow toward that region of the earth which is nearest to the sun, they must have both a diurnal and a seasonal periodicity. Both of these periodicities have long been known, not only in earth-currents and atmospheric potential gradients, but in the variation of the magnetic elements of the earth's field as well. If all, or any, of these phenomena are due to a shifting of an electric charge upon the earth, it must follow that the electric potential of the earth *at any given place* must also undergo diurnal and seasonal variations in magnitude. It was with the hope of detecting such a variation in earth potential at Palo Alto that the investigation herein described was undertaken.

If there is a permanent difference of electrical potential between the day and night sides of the earth, it would seem that if an uncharged conductor were insulated from the earth in the day time it might show a different potential from the earth at night; or since any place upon the earth is continuously moving toward or from the point nearest the sun, such a body might be expected to show a change of potential relative to the earth from hour to hour.

The experiment was first tried by connecting one pair of quadrants of a Dolezalek electrometer to the earth through the water system of Palo Alto and the other pair to an insulated conductor surrounded by a wire screen and placed in a closed closet. The electrometer needle was suspended by a quartz fiber, and its insulation was sufficiently good so that it needed recharging only once in two or three days. The metal case of the electrometer and the wire screen surrounding the insulated conductor were connected to earth through the city water system.

This apparatus was observed visually at frequent intervals for more than a month, the observations being sometimes continued for 24 hours at a time. A variation in potential between the earthed quadrants and the quadrants connected to the insulated conductor was plainly visible on every day of observation, and on some days the variation was several volts. The curve A, shown in Figure 1, gives the mean variation in

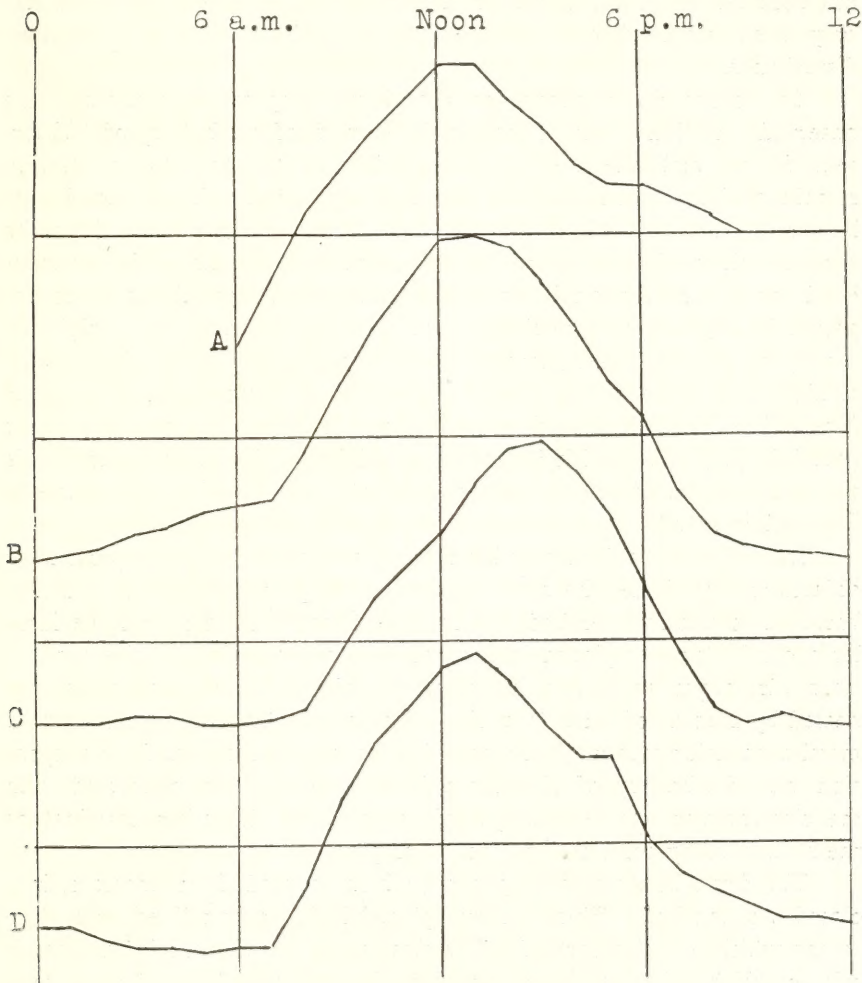


FIGURE 1.

Mean diurnal variation of earth potential at Palo Alto.

Curve A, diurnal variation from April 23 to May 20, 1920.

Curve B, mean diurnal variation from Aug., 1920, to July, 1921.

Curve C, mean diurnal variation from Sept., 1921, to Aug., 1922.

Curve D, mean diurnal variation from Sept., 1922, to Aug., 1923.

potential difference between the two pairs of electrometer quadrants between the hours of 6 A. M. and 9 P. M. for twenty days between April 23 and May 22, 1920, during which time the average rate of variation was more than .4 volt between the hours specified. During these observations the electrometer was set up in a room on the third floor of my house. In the case of the photographic records since collected the electrometer has been set up near the ground, and so great a range of variation has only been recorded at the times of unusual electric and magnetic disturbance.

In the experiment above described it was impossible to attribute the observed variation to any change in the e. m. f. of the battery of 100 dry cells from which the electrometer needle was charged, as the battery remained disconnected from the needle except for the single second once in two or three days while the needle was being charged. In order to be sure that the variation was not due to a temperature change in the insulated conductor (though it was of many times the magnitude to be expected in any temperature change) this conductor, which was originally a copper cylinder, was replaced by a coil of copper wire which was suspended in a dilute water solution of copper sulphate in a glass Dewar flask. The Dewar flask had a metal case, and this was placed in a larger porcelain jar, from which it was insulated by blocks of paraffine. This conductor was used in making the observations upon which the curve in Figure 1 is based.

In order to avoid all possible inductive effects of moving persons or objects in my house, the apparatus was set up in a small room in my barn. The electrometer had a wire cage placed around it and the insulated conductor was placed in another wire cage resting on the ground. Both wire cages, as well as the metal case of the electrometer, were connected by a soldered wire to a city water pipe. An electrometer with a metal suspension was used in place of the one with a quartz fiber suspension, and the battery of 100 dry cells was permanently connected with the electrometer needle through this suspension, the other terminal of the battery being connected to the water pipe.

The dry cells were set in asphalt, which covered the connectors, in a closed wooden box. This box was placed inside a box lined with wire screen which was also earthed. The electrometer needle carried a concave mirror which reflected the image of an incandescent lamp filament to a strip of sensitized paper upon a revolving drum, both the lamp and drum being about one meter distant from the electrometer. When a single dry cell was introduced between the electrometer case, to which one pair of quadrants was attached, and the ground, the image of the lamp filament was deflected about 6 cms. on the photographic paper.

This arrangement of apparatus was used continuously for one year, from August, 1920, to July, 1921. The mean monthly values of the diurnal variations of the electrometer readings, expressed in terms of the deflection caused by introducing one millivolt between the electrometer case with its attached quadrants and the earth, are shown in Table I. The graph representing the mean yearly value of the diurnal variation is shown in curve B, Figure 1.

TABLE I.

*Monthly Mean Diurnal Variation of Earth Potential for August, 1920-July, 1921.*

| A. M.       | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | Noon |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Aug. ....   | -15 | -14 | -9  | -5  | -3  | -3  | -3  | +26 | +38 | +39 | +35 | +27  |
| Sept. ....  | -22 | -19 | -17 | -14 | -12 | -12 | -10 | +10 | +29 | +41 | +38 | +32  |
| Oct. ....   | -15 | -12 | -8  | -9  | -6  | -3  | -1  | -1  | +18 | +32 | +40 | +41  |
| Nov. ....   | -22 | -15 | -12 | -10 | -6  | -2  | -1  | +4  | +7  | +15 | +27 | +36  |
| Dec. ....   | -19 | -17 | -14 | -7  | -1  | +3  | +7  | +7  | +8  | +12 | +20 | +32  |
| Jan. ....   | -16 | -16 | -15 | -13 | -11 | -10 | -10 | -11 | -10 | -3  | +16 | +36  |
| Feb. ....   | -39 | -36 | -35 | -37 | -35 | -35 | -34 | -33 | -17 | +10 | +34 | +57  |
| March. .... | -28 | -28 | -24 | -24 | -22 | -19 | -18 | -13 | +3  | +21 | +33 | +37  |
| April. .... | -10 | -10 | -8  | -7  | -5  | -4  | -5  | +15 | +26 | +24 | +20 | +18  |
| May. ....   | -4  | -7  | -8  | -9  | -10 | -10 | -10 | -8  | -2  | 0   | +1  | 0    |
| June. ....  | -8  | -6  | -3  | -7  | -6  | -2  | -9  | -12 | 0   | +7  | +6  | +7   |
| July. ....  | -9  | -10 | -14 | -17 | -18 | -18 | -19 | -11 | -6  | 0   | +10 | +20  |
| Mean. ....  | -17 | -16 | -14 | -13 | -11 | -10 | -9  | -2  | +8  | +16 | +23 | +29  |
| P. M.       | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12   |
| Aug. ....   | +17 | +13 | +4  | -1  | -12 | -6  | -23 | -27 | -23 | -22 | -19 | -19  |
| Sept. ....  | +28 | +27 | +26 | +20 | +8  | -2  | -17 | -29 | -30 | -29 | -27 | -26  |
| Oct. ....   | +39 | +31 | +24 | +14 | -7  | -12 | -28 | -34 | -33 | -28 | -23 | -22  |
| Nov. ....   | +40 | +34 | +25 | +12 | -4  | +1  | -15 | -19 | -24 | -24 | -24 | -26  |
| Dec. ....   | +33 | +30 | +19 | +11 | +5  | -5  | -16 | -20 | -20 | -20 | -21 | -20  |
| Jan. ....   | +47 | +49 | +35 | +22 | +12 | -1  | -12 | -17 | -21 | -20 | -18 | -18  |
| Feb. ....   | +70 | +77 | +65 | +53 | +41 | +21 | +5  | -4  | -22 | -28 | -32 | -37  |
| March. .... | +38 | +36 | +34 | +27 | +19 | +11 | 0   | -10 | -17 | -20 | -24 | -28  |
| April. .... | +15 | +12 | +9  | +6  | -3  | -7  | -17 | -18 | -15 | -14 | -12 | -10  |
| May. ....   | +4  | +12 | +16 | +16 | +13 | +7  | +5  | +5  | +5  | +4  | +4  | -2   |
| June. ....  | 0   | -8  | -2  | +6  | +17 | +19 | +12 | -1  | -4  | +1  | -1  | 0    |
| July. ....  | +24 | +21 | +14 | +11 | +10 | +5  | +10 | +11 | +6  | -3  | -5  | -6   |
| Mean. ....  | +30 | +28 | +22 | +16 | +8  | +3  | -8  | -14 | -16 | -17 | -17 | -18  |

While the reality of a diurnal variation of earth potential at the place of experiment seemed to be beyond question, there was still much skepticism expressed by other physicists to whom the results of the investigation were reported. Perhaps the most common objection was based upon

a belief in the impossibility of a change in electrical potential of a conductor inside of and in electrical contact with a closed hollow conductor. So it was decided to put the question to a still further test. Accordingly a new cage was built which was sufficiently large to contain the electrometer, the insulated conductor and the battery by which the electrometer needle was charged. This cage was 8 feet by 9 feet on the ground and 7 feet high. It was set up in a room 8 feet by 16 feet in dimensions without a floor, so the bottom side of the cage rested immediately upon the ground. The cage was built of galvanized wire netting, the different strips being soldered together. When the door was closed, there were

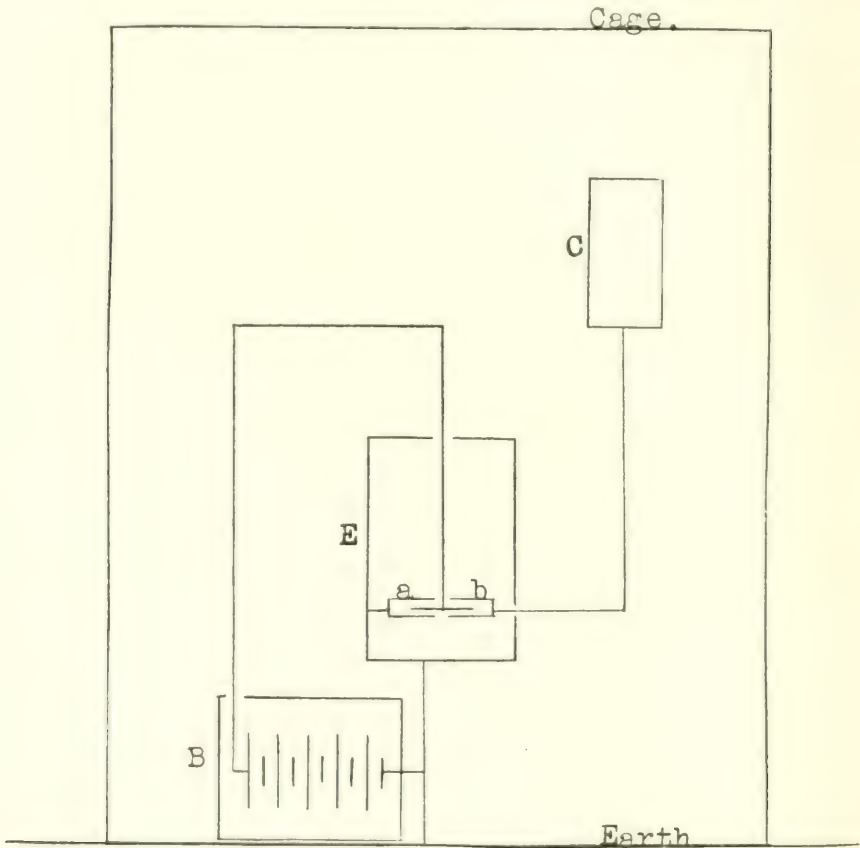


FIGURE 2.

Diagram of electrometer connections for measuring variations of earth potential.

E indicates the electrometer, of which a and b are the quadrant pairs, B, the battery from which the electrometer needle is charged, and C, the insulated conductor which is connected to one pair of quadrants.

no openings into it except where two 4-inch by 4-inch wooden posts passed through it into the ground. Its screening effect was tested with a gold leaf electroscope, which showed no deflection when a high static charge was brought within 8 inches of it on the other side of the screen.

The electrometer was supported upon a wooden plank which rested upon the two posts mentioned above. One pair of quadrants and the metal case of the instrument were connected by a soldered wire to the city water system. The other pair of quadrants was connected by a copper wire to the insulated conductor described above, which was suspended near the center of the cage. The box of dry cells by which the electrometer needle was charged was placed in a zinc-lined box which rested upon the bottom of the cage below the electrometer. To protect it from temperature changes, the wooden box containing the dry cells was surrounded by a layer of cork cuttings about two inches thick between it and the metal-lined box. One of the battery terminals was permanently connected to the electrometer suspension and the other was connected to the zinc-lined box, the large cage and the water pipe. The lamp and recording apparatus were placed outside the large cage. A diagram to represent the electrometer connections is shown in Figure 2.

With this arrangement, the electrometer and the insulated conductor remained continuously in a closed, earthed, hollow conductor, and one pair of quadrants remained in electrical contact with the inside of the hollow conductor. The whole apparatus was effectually screened from the induction of any outside charge. The insulated conductor to which one pair of quadrants was attached was, in the beginning, at the same potential as the pair of earthed quadrants. It could not change its electrical condition. Any leakage through its insulation would merely serve to keep it at the same potential as the earthed pair of quadrants. Any potential difference arising between the two pairs of quadrants was necessarily due to a change in potential of the pair which was connected to the outer cage and the earth. With this arrangement a diurnal variation of potential difference between the two pairs of quadrants has been almost continuously recorded for two years. During that time there has not been a record of a single day without the variation.

Photographic records of the diurnal variation in earth potential at Palo Alto were made with the apparatus in the large cage described above from September, 1921, to August 1, 1923, and the monthly mean values of the diurnal variation for this period are shown in Tables II and III. The yearly mean values are shown in curves C and D in Figure 1.

TABLE II.

*Monthly Mean Diurnal Variation of Earth Potential for the Year  
September, 1921-August, 1922.*

| A. M.      | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | Noon |
|------------|------|------|------|------|------|------|------|------|------|------|------|------|
| Sept.....  | -189 | -183 | -163 | -170 | -186 | -183 | -188 | -177 | -76  | +77  | +166 | +261 |
| Oct.....   | -34  | -63  | -103 | -131 | -158 | -175 | -195 | -173 | -60  | +29  | +58  | +136 |
| Nov.....   | -35  | -6   | +18  | +49  | +71  | +75  | +87  | +75  | +50  | +44  | +36  | 0    |
| Dec.....   | -20  | -11  | -2   | -3   | -5   | +10  | +14  | +5   | -1   | -6   | 0    | +25  |
| Jan.....   | -55  | -47  | -41  | -40  | -38  | -43  | -41  | -41  | -36  | -25  | -15  | +12  |
| Feb.....   | -15  | -11  | -9   | -10  | -7   | -5   | -6   | -17  | -18  | -6   | +12  | +20  |
| March..... | -19  | -23  | -21  | -20  | -20  | -18  | -16  | -11  | +6   | +23  | +34  | +32  |
| April..... | -24  | -27  | -29  | -32  | -32  | -33  | -52  | +8   | +52  | +66  | +66  | +62  |
| May.....   | -13  | -15  | -17  | -15  | -22  | -21  | -5   | +1   | +4   | +4   | 0    | +4   |
| June.....  | -6   | -6   | -6   | -6   | -8   | -11  | +9   | 0    | +1   | 0    | -4   | -3   |
| July.....  | -8   | -7   | -6   | -3   | +3   | +7   | +17  | -1   | +3   | +3   | +3   | -2   |
| Aug.....   | -28  | -29  | -30  | -31  | -35  | -36  | -48  | -35  | +10  | +24  | +30  | +32  |
| Mean.....  | -37  | -36  | -34  | -34  | -36  | -36  | -35  | -30  | -5   | +19  | +32  | +48  |
| P. M.      | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   |
| Sept.....  | +353 | +474 | +500 | +427 | +250 | +97  | -42  | -177 | -215 | -199 | -235 | -216 |
| Oct.....   | +179 | +212 | +244 | +240 | +194 | +45  | -51  | -122 | -60  | 0    | +1   | -1   |
| Nov.....   | -2   | +6   | -12  | -37  | -52  | -25  | -28  | -36  | -74  | -76  | -71  | -53  |
| Dec.....   | +41  | +34  | +14  | +5   | 0    | -6   | -19  | -17  | -16  | -20  | -16  | -14  |
| Jan.....   | +73  | +84  | +92  | +84  | +86  | +57  | +39  | +19  | -10  | -22  | -46  | -56  |
| Feb.....   | +32  | +35  | +26  | +25  | +20  | +15  | -2   | -15  | -13  | -11  | -21  | -17  |
| March..... | +34  | +34  | +28  | +24  | +20  | +9   | -7   | -17  | -21  | -26  | -20  | -20  |
| April..... | +69  | +75  | +78  | +81  | +69  | +13  | +16  | -6   | -12  | -16  | -20  | -22  |
| May.....   | +10  | +16  | +23  | +28  | +22  | +18  | +10  | +3   | -2   | -5   | -8   | -11  |
| June.....  | +1   | +4   | +14  | +16  | +10  | +4   | 0    | -5   | -6   | -11  | -7   | -6   |
| July.....  | -2   | +1   | +8   | +11  | +7   | +2   | -1   | -4   | -6   | -6   | -7   | -9   |
| Aug.....   | +36  | +34  | +29  | +24  | +21  | +23  | +20  | +14  | +15  | -2   | -7   | -20  |
| Mean.....  | +69  | +84  | +87  | +76  | +54  | +21  | -5   | -30  | -35  | -33  | -38  | -37  |

The units used in the above table are tenths of millimeters on the record sheet. To reduce them to the units used in Table I, they should be multiplied by 1.6.

TABLE III.

*Monthly Mean Diurnal Variation of Earth Potential for September, 1922-August, 1923*

| A. M.      | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | Noon |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Sept.....  | -21 | -39 | -54 | -61 | -67 | -66 | -85 | -45 | +13 | +29 | +40 | +58  |
| Oct.....   | +1  | -6  | -4  | -6  | -8  | -9  | -10 | -10 | -11 | -3  | +9  | +17  |
| Nov.....   | +3  | -9  | -20 | -43 | -56 | -66 | -83 | -72 | -43 | -24 | -17 | +21  |
| Dec.....   | -10 | -11 | -13 | -14 | -14 | -15 | -14 | -12 | -8  | -2  | +5  | +12  |
| Jan.....   | -7  | -9  | -12 | -12 | -14 | -15 | -14 | -15 | -11 | -7  | -1  | +8   |
| Feb.....   | -12 | -14 | -14 | -13 | -11 | -8  | -7  | -7  | -8  | -14 | -16 | -11  |
| March..... | -15 | -13 | -11 | -10 | -9  | -10 | -10 | -2  | +6  | +9  | +11 | +14  |
| April..... | -17 | -13 | -10 | -7  | -4  | -3  | +4  | +11 | +18 | +23 | +33 | +42  |
| May.....   | -16 | -10 | -5  | -2  | +2  | +7  | +19 | +24 | +31 | +33 | +35 | +35  |
| June.....  | -13 | -10 | -7  | -4  | +1  | +5  | +8  | +15 | +24 | +25 | +28 | +25  |
| July.....  | -20 | -17 | -13 | -4  | 0   | +7  | +18 | +23 | +33 | +35 | +34 | +29  |
| Aug.....   | -16 | -15 | -12 | -8  | -6  | -4  | -6  | +15 | +28 | +71 | +76 | +59  |
| Mean.....  | -12 | -14 | -15 | -15 | -16 | -15 | -15 | -6  | +6  | +15 | +20 | +26  |
| P. M.      | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12   |
| Sept.....  | +55 | +49 | +32 | +26 | +22 | +27 | +30 | +29 | +25 | +18 | +5  | -11  |
| Oct.....   | +23 | +13 | -3  | -5  | -7  | -1  | -6  | -1  | +3  | +7  | +11 | +3   |
| Nov.....   | +57 | +64 | +55 | +51 | +80 | +37 | +26 | +12 | +15 | +8  | +4  | +4   |
| Dec.....   | +16 | +16 | +17 | +14 | +8  | +19 | +13 | +4  | 0   | -3  | -6  | -8   |
| Jan.....   | +14 | +14 | +12 | +16 | +15 | +9  | +14 | +13 | +7  | +2  | +1  | -4   |
| Feb.....   | -1  | +6  | +17 | +26 | +32 | +29 | +22 | +13 | +6  | -1  | -4  | -9   |
| March..... | +20 | +21 | +24 | +25 | +22 | +8  | -1  | -8  | -15 | -20 | -21 | -19  |
| April..... | +43 | +36 | +22 | +8  | +7  | -24 | -30 | -31 | -32 | -28 | -25 | -20  |
| May.....   | +32 | +26 | +16 | +2  | +14 | -29 | -36 | -38 | -37 | -38 | -28 | -22  |
| June.....  | +22 | +21 | +19 | +14 | 0   | -20 | -25 | -30 | -31 | -30 | -25 | -17  |
| July.....  | +26 | +22 | +19 | +9  | -5  | -15 | -25 | -30 | -34 | -32 | -28 | -24  |
| Aug.....   | +30 | -3  | -17 | -29 | -28 | -23 | -30 | -21 | -17 | -17 | -16 | -14  |
| Mean.....  | +28 | +24 | +18 | +13 | +13 | +1  | -4  | -7  | -9  | -11 | -11 | -12  |

### The Bearing of This Investigation Upon Electrical Theory

Two facts, both of which are fundamental in electrical theory, seem to be established by this investigation. One of these is that there is a diurnal variation in the electrical potential of the earth *at a given place*, a fact which may also be inferred from the diurnal variations of the earth-currents and atmospheric potential gradients. The other is the fact that while an uninsulated body inside a closed hollow conductor is not at all affected by any charge upon the outer conductor, and that whatever charges are induced upon the outer conductor are so distributed that they shield the inner conductor from the inductive action of surrounding

charges, still, an increase or decrease in the electrical potential of the earth in the vicinity of the experiment will cause a corresponding change in the enclosed conductor.

In the light of these experiments, the well-known law of Cavendish and Faraday may be stated as follows: *An uninsulated conductor enclosed in another hollow conductor remains in electrical equilibrium with the earth in its vicinity, regardless of electrical charges upon the hollow conductor in which it is enclosed, or upon other conductors in its vicinity.*

It follows that if the earth is an electrified planet, as many eminent physicists have believed, a body inside of and in electrical contact with a closed hollow conductor is not in a condition of absolute electrical neutrality.

The actual magnitude of the variation in earth potential as shown by these records is unknown. While the sensitivity of the electrometer for a given potential difference between its quadrants may be relied upon to remain constant, its sensitivity to an electromotive force introduced between its case, to which one pair of quadrants is attached, and the earth varies with the distance and capacity of the insulated conductor which is connected to the other pair of quadrants. Thus, when one pair of quadrants was kept insulated with no other capacity attached to it, the introduction of a dry cell between the electrometer case and the outer cage caused a deflection of only two or three millimeters on a scale at a distance of one meter from the instrument. When the insulated quadrants were connected to the insulated conductor used in making the records, and this conductor was placed very close to the quadrants to which it was connected, the deflection was still only a few millimeters. With the insulated capacity suspended near the center of the large cage, the deflection for a single dry cell used as above was about 6 cms. It follows as a matter of course from the known laws of electrostatic induction that the farther the insulated capacity can be placed from its connected quadrants and from the earthed conductors around it, the greater will be the sensitivity of the instrument to a given change in earth potential. For the above reasons, the sensitivity of the electrometer was not the same under the different conditions under which the experiment was carried on, and the actual magnitudes of the quantities recorded in the different years are not strictly comparable.

#### Seasonal Changes in Diurnal Variation of Earth Potential

It is plain that if there is a shifting of the earth's negative charge due to the induction of a similar charge upon the sun, not only will the night side of the earth remain electronegative to the day side, but the winter hemisphere of the earth will be electronegative to the summer hemi-

sphere. This should cause a difference in the curves representing the diurnal variation at different seasons of the year. Thus, during the summer the principal induced charge on the night side of the earth will

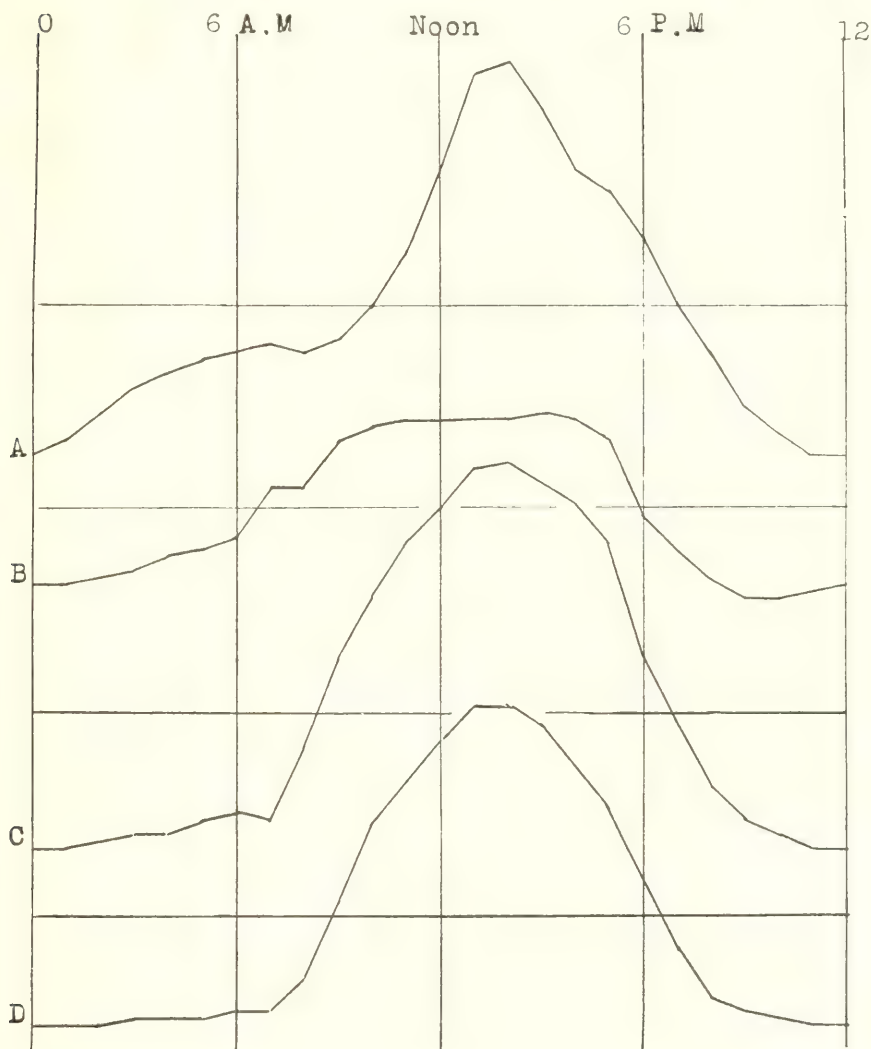


FIGURE 3.

Seasonal changes in the diurnal variation of earth potential at Palo Alto.

Curve A represents the mean diurnal variation at the time of the winter solstice, Curve B, at the time of the summer solstice, Curve C, at the time of the vernal equinox, and Curve D shows the mean diurnal variation for three years.

remain south of the Equator, and the difference between the day and night potential will not be so great as in the winter time.

In Figure 3 are shown the curves representing the mean diurnal variation at the times of winter solstice, Curve A, the summer solstice, Curve B, and the vernal equinox, Curve C, for the three years covered by this report. The winter curve is taken to include the months November, December and January; the summer curve is for the months May, June and July, and the equinoctial curve is for the months February, March and April. Each curve accordingly represents the mean diurnal variation for nine months. The curve for the autumnal equinox is not shown for the reason that the months of September and October, 1921, were very much disturbed, so that their range of variation was five or six times as great as for the same months in the other years. The records of these two months would accordingly make the range of the autumnal equinoctial curve about three times as great as any of the other curves in Figure 3.

Curve D, in Figure 3, shows the mean diurnal variation for the three years of this report. The resemblance of this curve to the one for the vernal equinox is, as we should expect, very marked, while the short and steep electropositive maximum in winter when the days are short is strongly contrasted with the long, low electropositive maximum during the longer days of summer.

### Auroras and Electrical Potential Variations

In *Science* of December 23, 1921, I published a short paper on the earth potential disturbances at the time of the great aurora of May 14, 1921. In that article I showed curves giving the potential variation at Palo Alto for a number of days preceding and a number of days following the aurora. The feature of this electrical disturbance which was most surprising to me was the fact that it mostly preceded the aurora, and that for several days following the aurora the diurnal variation was very small. The most striking feature of the disturbance occurred at about 3 o'clock on the afternoon of May 11, when the electrometer record changed within a few minutes from +40 to -235 scale divisions. From this time until about 4 A. M. of May 12, the electrometer record showed a gradual return to the positive side.

The mean range of diurnal variation for the five days immediately preceding the aurora was 154 scale divisions, the maximum, which occurred on the 11th, being 305, and the minimum, 95. The mean range of diurnal variations for the five days following the aurora was 34 scale divisions, the maximum being 40, and the minimum, 30.

On the day of the aurora I was away from home, and my driving

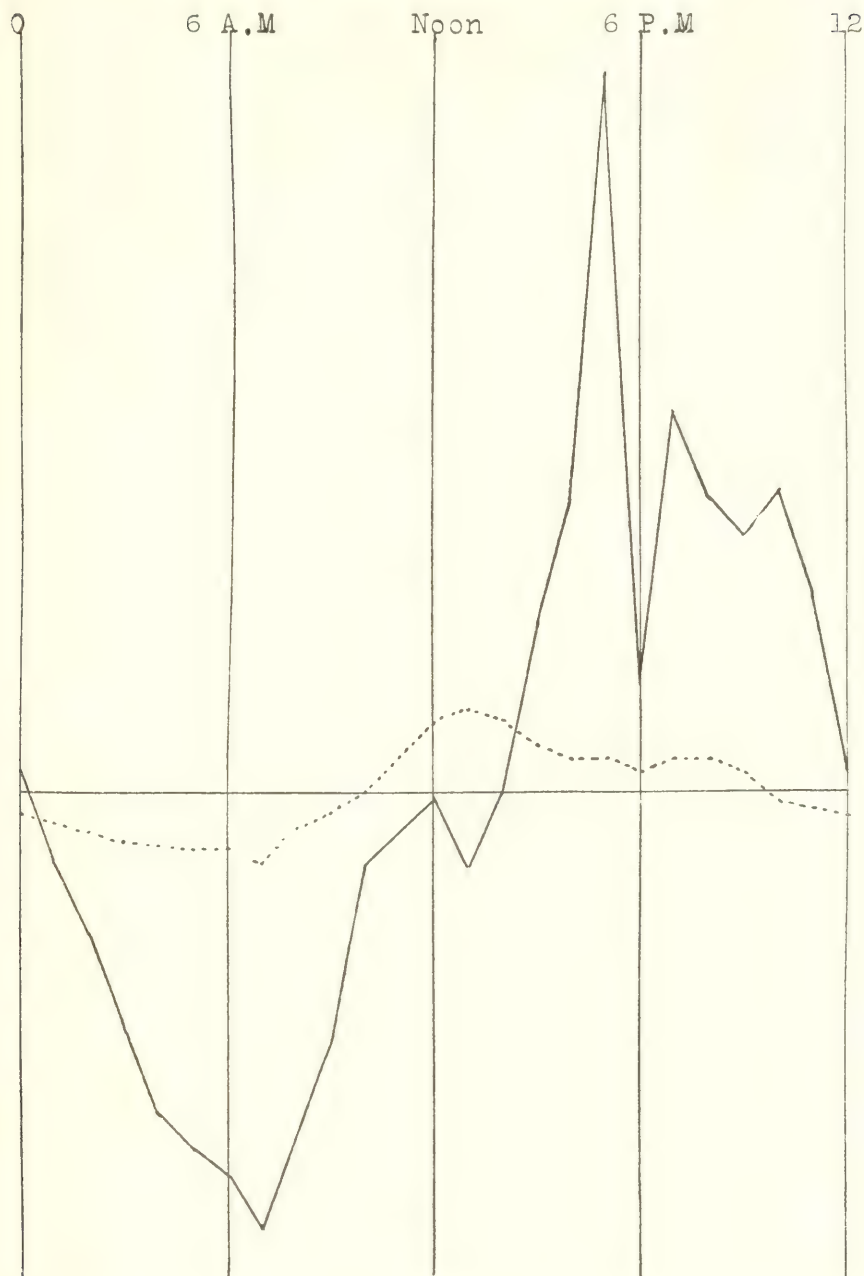


FIGURE 4.

Effect of the aurora of July 10, 1921, on the diurnal variation of earth potential at Palo Alto.

The solid curve shows the diurnal variation for the five days preceding the aurora and the dotted curve for the rest of the month.

clock ran down at about the time of the appearance of the aurora. The recording sheet, which remained stationary from about 8 o'clock on the evening of the 14th until 1 o'clock the morning of the 15th, did not indicate an excessive variation during that time.

On the morning of July 10, 1921, a brilliant aurora was reported from Northern California. For about a week preceding this there had been an unusually great and irregular diurnal variation of earth potential at Palo Alto. This irregularity began on July 2, about 6 P. M., with an abrupt change from +360 to -340 scale divisions on my record. On July 4, the range was not very great, but on the 5th and 7th it went off my recording sheet. On July 10, at the time when the aurora was reported, there was no marked disturbance, and immediately afterward it became less than usual.

In Figure 4 are shown two curves, of which the continuous curve represents the mean diurnal variation of earth potential at Palo Alto for the five measurable days immediately preceding the aurora of July 10, and the dotted curve represents the mean diurnal variation for all the other days of the month expressed in the same units.

Similar potential variation disturbances have occurred at other times, notably in the early days of September and October, 1921, without being accompanied by auroras; but they have always been accompanied by marked magnetic disturbances.

#### Lunar Diurnal Variations of Earth Potential at Palo Alto

In two papers read before the American Physical Society, abstracts of which were published in *The Physical Review* of October, 1921, and May, 1922, I have called attention to a periodic variation of earth potential at Palo Alto which corresponds with the change in the hour angle of the moon. These two reports covered eight synodic periods up to December, 1921. In 1922, the lunar diurnal variation was computed for eight months by Chapman's method\* of subtracting the mean variation at a given hour for the whole month from each of the single variations at that same hour, and distributing the residuals, either positive or negative, to the proper hour of the lunar day. This method assumes that the monthly mean represents the true solar variation, and that variations from this mean include whatever effect the moon may have upon the phenomenon under consideration.

In determining the lunar day, the hour of the solar day nearest to the upper culmination of the moon for that day was taken as the twelfth hour of the lunar day, and the other hours of the solar day were dis-

\* *Phil. Trans.*, 214, 295-317 (1914).

tributed with reference to this hour. This does not give the true lunar hours, but approximates closely enough to them for the present purpose.

The mean monthly variation for each lunar hour of the eight months, expressed in millimeters on the record sheet, is shown in Table IV. It will be seen that the lunar variations are small compared with those due to the sun, being from one-seventh to one-tenth of the magnitude of the latter; but there can be no doubt of their existence. The measurements of the record sheets were made to one-half millimeter. All the measurements and calculations were made by myself, and I am fully convinced of their substantial accuracy.

It is to be expected that the lunar variations measured in this way will show relatively greater irregularities than will the solar variations, since the residuals that are left after subtracting the monthly mean variations due to the sun contain all the irregularities of the solar curves, whether due to the moon or not; hence a long series of observations is needed to determine the true potential variation due to the moon. This report is intended merely to establish the existence of such a variation and to give its approximate character.

In Table IV the means of the three series of determinations of the lunar variation are given, and in Figure 5 is given a curve showing graphically the mean of these three determinations of the lunar diurnal variation of earth potential at Palo Alto.

TABLE IV.

| Hour         | 1  | 2  | 3  | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | U. C. |
|--------------|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-------|
| Jan. '22.... | -9 | -4 | -4 | -11 | -12 | -11 | -8  | -6  | -5  | +4  | +14 | +26   |
| Feb., "....  | -1 | -8 | -6 | -4  | -2  | -4  | -1  | +8  | +10 | +17 | +17 | +11   |
| Mar., "....  | -2 | -3 | -4 | -5  | -3  | -2  | -2  | -5  | -1  | 0   | +5  | +6    |
| Apr., "....  | -3 | -4 | -5 | -5  | 0   | +10 | +10 | +10 | +10 | +7  | +5  | +1    |
| May, "....   | -1 | +1 | +2 | +2  | 0   | 0   | -1  | +1  | +2  | +2  | +3  | +2    |
| June, "....  | -7 | -9 | -6 | -6  | -5  | -4  | -3  | -2  | +1  | +2  | +2  | +4    |
| July, "....  | 0  | 0  | -1 | -4  | -6  | -3  | -3  | -1  | -2  | +3  | +6  | +5    |
| Aug., "....  | -3 | -7 | +7 | +3  | -7  | -6  | -17 | -17 | +3  | 0   | +4  | -3    |
| Mean.....    | -3 | -4 | -2 | -4  | -4  | -2  | -3  | -1  | +2  | +4  | +7  | +6    |
| 1st Series.. | -3 | -3 | -3 | -4  | -2  | -1  | +1  | +2  | +3  | +4  | +3  | +4    |
| 2nd Series.. | +1 | +1 | +1 | +1  | +2  | +1  | +1  | +1  | +2  | +2  | +1  | +1    |
| Sum of 3...  | -5 | -6 | -4 | -7  | -4  | -2  | -1  | +2  | +7  | +10 | +11 | +11   |

TABLE IV—Continued

| Hour         | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  | 21  | 22  | 23  | 24  |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Jan.....     | +28 | +29 | +26 | +26 | +15 | +1  | +1  | -4  | -13 | -22 | -30 | -37 |
| Feb.....     | +7  | +7  | +3  | +4  | +2  | -13 | -12 | -12 | -15 | -10 | -8  | 0   |
| March.....   | +8  | +9  | +8  | +4  | -4  | -3  | -2  | 0   | -2  | -1  | -2  | -3  |
| April.....   | +1  | +7  | +7  | +4  | +2  | -2  | -3  | -6  | -2  | -1  | 0   | -5  |
| May.....     | +1  | -1  | -2  | -2  | -2  | -1  | 0   | -2  | -3  | -2  | 0   | -3  |
| June.....    | +4  | +3  | +4  | +3  | +3  | +4  | +4  | +2  | 0   | -3  | -4  | -7  |
| July.....    | +5  | +2  | 0   | 0   | +2  | 0   | +1  | -1  | -2  | +1  | -1  | +1  |
| Aug.....     | +3  | +1  | -1  | +11 | +14 | +4  | +1  | +4  | +7  | +6  | -1  | -7  |
| Mean.....    | +7  | +7  | +6  | +6  | +4  | -1  | -1  | -2  | -4  | -4  | -6  | -8  |
| 1st Series.. | +4  | +2  | +3  | +2  | +1  | 0   | -1  | 0   | -1  | -3  | -3  | -3  |
| 2nd Series.. | +1  | 0   | -1  | -1  | -1  | -1  | -3  | -3  | -1  | -2  | -2  | -1  |
| Sum of 3...  | +12 | +9  | +8  | +7  | +4  | -2  | -5  | -5  | -6  | -9  | -11 | -12 |

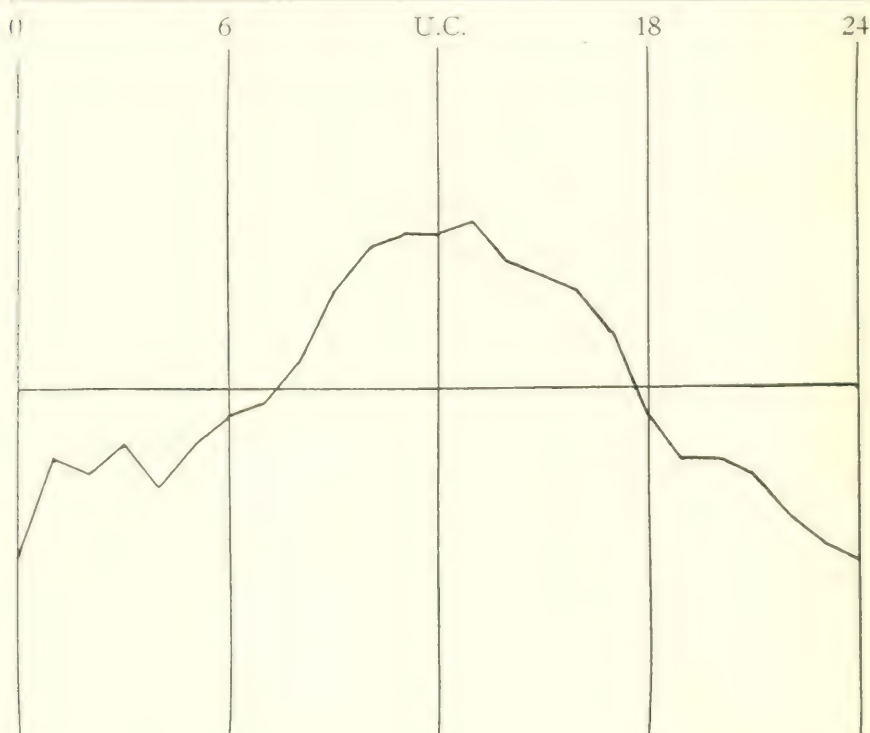


FIGURE 5.

Figure 5 shows the mean lunar diurnal variations of earth potential at Palo Alto for sixteen synodic periods.

### Earth-Current Variation

Since a diurnal variation of the earth potential at a given place seems necessarily to be brought about by earth-currents, it is important to know the relation between the earth potential variations and the variations of the earth-currents at a given place. Through the generosity of The Pacific Telephone and Telegraph Company I was given a wire from a ground at Menlo Park, about two miles distant, to my station in Palo Alto. When a galvanometer was introduced into this line, it was found that the currents from the Palo Alto trolley lines made any determination of the character of the earth-currents in the Menlo Park line exceedingly difficult, if not impossible. Later, the telephone company gave me another wire to a ground about two miles south of the ground at Menlo Park, so that the Palo Alto ground could be cut out entirely.

When a galvanometer was introduced into this line, it was found that the N-S earth-current was too strong for any ordinary galvanometer, even with a resistance of 1,000 ohms in the line, and that it was very unsteady, the galvanometer needle seldom remaining at rest for a single second. In addition to the irregular disturbances there was a very conspicuous diurnal variation in current, the weakest current occurring about noon, and the strongest in the morning and evening.

In order to make possible a photographic record, I had a d'Arsonval galvanometer of low sensitivity provided with a moving coil of only a few turns of No. 20 wire, and suspended inside a brass beaker which was placed between the poles of the galvanometer magnet and was filled with heavy machine oil. The viscosity of the oil was great enough to cut down the time of one oscillation of the galvanometer coil to about ten minutes. With this instrument it was possible to record the vibrations photographically upon the drum used for recording the variations in earth potential. This drum is 48 centimeters in circumference and makes one revolution in 24 hours, thus advancing the photographic sheet at the rate of one millimeter in three minutes.

Records have been obtained with this apparatus since November 1, 1922. During this period there have been a number of occasions when the beam of light from the galvanometer mirror has gone off the recording sheet (which is six inches wide) on both sides for several days at a time. There have been times when the galvanometer coil has swung through more than 90 degrees for several hours at a time. As it is now set up, with 400 ohms resistance in the line and a shunt around this resistance and the galvanometer, the daily range on the quietest days is from two to three centimeters. During most of the period for which I have records, the range has been from four to five times this great, owing to the greater sensitivity of the apparatus.

In Table V are given the monthly mean diurnal variations for all the days during which the record was measurable, 178 days, in all. This variation is also shown graphically in Curve A, Figure 6, where it is compared with the diurnal variation in earth potential for the same period, Curve B.

The direction of the current in the earth between my two grounds is about  $21\frac{1}{2}^\circ$  west of south. Since the magnetic declination is  $19^\circ$  east, the current is within one or two degrees of the magnetic meridian, and is nearly perpendicular to the shores of San Francisco Bay, the marshes of which are distant about one and one-half miles from the northerly ground.

TABLE V.

*Mean Diurnal Variation of N-S Earth-Current.*

| A. M.      | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | Noon |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Nov.....   | +14 | +12 | +11 | +10 | +8  | +14 | +5  | +1  | -3  | -12 | -19 | -25  |
| Dec.....   | +10 | +8  | +6  | +4  | +2  | +8  | -1  | -1  | -2  | -7  | -9  | -12  |
| Jan.....   | +7  | +5  | +4  | +4  | +3  | +7  | +4  | +4  | +4  | +4  | -1  | -6   |
| Feb.....   | -3  | -14 | -22 | -17 | -15 | +11 | +37 | +46 | +23 | -8  | -27 | -40  |
| March..... | +12 | 0   | -7  | -3  | -8  | +23 | +37 | +32 | +2  | -20 | -31 | -39  |
| April..... | +11 | +1  | -1  | 0   | -1  | +36 | +34 | +35 | +1  | -21 | -33 | -36  |
| May.....   | +14 | +8  | +1  | +3  | -1  | +35 | +34 | +17 | -7  | -26 | -34 | -33  |
| June.....  | -4  | +1  | +2  | +4  | 0   | +13 | +10 | +1  | -14 | -6  | -7  | -14  |
| July.....  | +9  | -5  | -8  | -8  | -9  | +27 | +36 | +23 | +6  | -15 | -23 | -25  |
| Aug.....   | +2  | +1  | -12 | -9  | -12 | +36 | +53 | +42 | -7  | -39 | -36 | -24  |
| Mean.....  | +7  | +2  | -3  | -1  | -3  | +21 | +25 | +20 | 0   | -15 | -22 | -25  |
| P. M.      | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12   |
| Nov.....   | -24 | -20 | -16 | -9  | +5  | +10 | +4  | +4  | +3  | +3  | +11 | +16  |
| Dec.....   | -14 | -11 | -1  | -8  | -7  | +7  | +8  | +3  | +4  | +3  | +6  | +11  |
| Jan.....   | -11 | -14 | -14 | -12 | -9  | -1  | +1  | +3  | +4  | +2  | +5  | +9   |
| Feb.....   | -39 | -26 | -27 | -10 | +5  | +53 | +23 | +9  | +11 | +18 | +6  | +4   |
| March..... | -36 | -24 | -18 | -7  | +16 | +34 | +15 | 0   | +3  | +5  | +8  | +12  |
| April..... | -36 | -34 | -23 | -7  | -7  | +35 | +16 | -1  | -2  | -1  | +1  | +9   |
| May.....   | -27 | -20 | -15 | -6  | -2  | +33 | +6  | -5  | -3  | -1  | +10 | +14  |
| June.....  | -16 | -10 | -1  | -1  | +24 | +16 | +3  | +2  | -6  | +1  | +1  | +1   |
| July.....  | -11 | -4  | +1  | +2  | +8  | +25 | +3  | +6  | -6  | -8  | +3  | +6   |
| Aug.....   | -14 | -4  | +3  | +9  | +9  | +20 | -1  | -11 | -7  | -4  | +1  | +6   |
| Mean.....  | -23 | -17 | -11 | -5  | +4  | +23 | +8  | +1  | 0   | +2  | +5  | +9   |

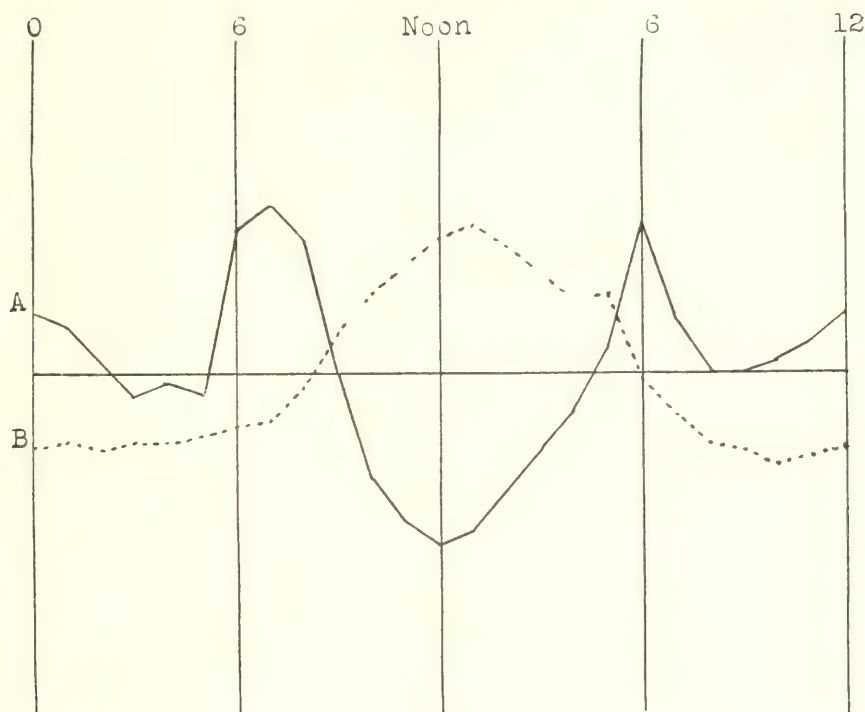


FIGURE 6.

Mean diurnal variation of N-S earth-current at Palo Alto.

Curve A indicates the mean diurnal variation of the N-S earth-current for 178 days from November, 1922, to August, 1923.

Curve B shows the mean diurnal variation of earth potential for the same period.

### Lunar Diurnal Variation of Earth-Currents

It has long been known that there is a lunar, diurnal variation of the magnetic elements of the earth's field. This fact is said to have been discovered by Kreil, in 1841. In his Bakerian Lecture published in Phil. Trans. of 1852, Gen. Sabine showed unquestionable effects of the influence of the moon on magnetic declination at Toronto, St. Helena and Hobarton. In Phil. Trans. 213, 214 and 218, Chapman discusses the lunar effect upon the magnetic elements and calculates the mean magnetic variation at Pola, Austria, and Pawlosk, Russia, for the years 1897-1903.

On page 892 of *Kosmische Physik*, Arrhenius discusses the moon's influence upon the atmospheric potential gradient, and says that there is an appreciable decrease in the potential gradient a short time before the upper culmination of the moon.

So far as I am informed, no lunar diurnal variation of earth-currents has hitherto been established, but the close relation which is known to exist between magnetic variations and earth-currents suggests that such a variation probably exists. I have accordingly undertaken to determine if such a lunar variation is observable in the earth-current records of Ebro Observatory.

The method used was to arrange the hourly records of magnitude of the N-S earth-current for one complete synodic period according to lunar hours and then to determine the mean variation for each hour of the lunar day from the mean of the whole period. In using this method it is neces-

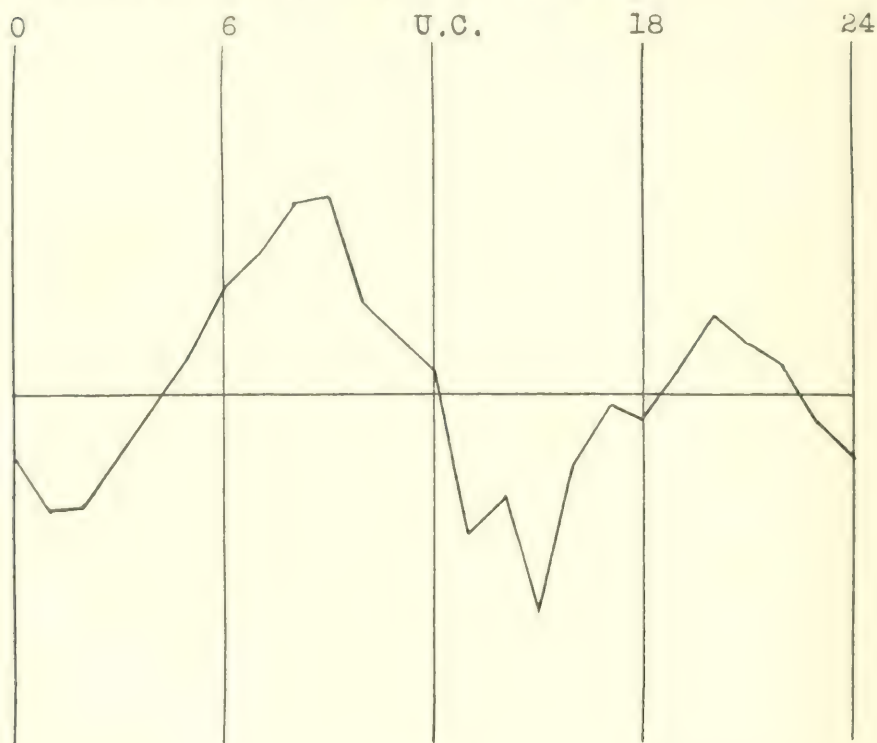


FIGURE 7.

Lunar diurnal variations of N-S earth currents at Ebro Observatory for nine synodic periods.

sary to select synodic periods for which there are no missing records, and, where it is possible, to use two successive synodic periods so that there shall be a whole number of both solar and lunar days. Nine complete synodic periods were used, viz., May-July, 1916, February-April, 1919, and October-December, 1920.

In the records used the potential difference in millivolts per kilometer between the two grounds is given instead of the current intensity through the galvanometer. For the whole period under consideration the mean value of this potential difference was 380.9 m.v./k.m. The mean variation from this value for each hour of the lunar day was as follows:

| Hour          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | U.C. |
|---------------|------|------|------|------|------|------|------|------|------|------|------|------|
| Variation . . | -3.3 | -3.2 | -1.9 | -0.3 | +0.9 | +2.9 | +4.0 | +5.4 | +5.6 | +2.6 | +1.6 | +0.7 |
| Hour          | 13   | 14   | 15   | 16   | 17   | 18   | 19   | 20   | 21   | 22   | 23   | 24   |
| Variation . . | -4.1 | -3.0 | -6.3 | -2.1 | -0.3 | -0.8 | +0.6 | +2.2 | +1.3 | +0.8 | -0.7 | -1.8 |

This variation is shown graphically in Figure 7.

### Magnetic Data

As has already been stated, this investigation was undertaken in consequence of a belief that the magnetic field of the earth is caused by the revolution of its negative charge. This being the case, it was thought possible that the electronegative side of the earth would show a stronger magnetic field than the electropositive side. A comparison of the curve for the diurnal variation of earth potential at Palo Alto with the curves for the diurnal variation of the north magnetic component at the Falmouth and Kew observatories seemed to favor this surmise.\* Accordingly, a magnetometer carrying a compound magnet supported by a bi-filar suspension was set up beside the electrometer which was used for recording the variations in earth potential, and the torsion head carrying the suspension was rotated until the north end of the magnet pointed west. The magnet was provided with a concave mirror which reflected a beam of light from the electrometer lamp upon the recording drum, so that the magnetic variation was recorded on the same sheet as the electrometer variations.

No determination of the magnetometer constants was made, and no corrections for temperature variations. The records were made from March 1, 1921, to August 1, 1922. They have all been measured and recorded, but the monthly mean of the diurnal variations has been computed for only eleven months. This eleven-month mean is shown in Curve A, Figure 8. Curve B, in the same figure, shows the three-year mean diurnal earth potential variation inverted for better comparison.

\* Sanford, *Phys. Rev.*, Feb., 1921 and April, 1921.

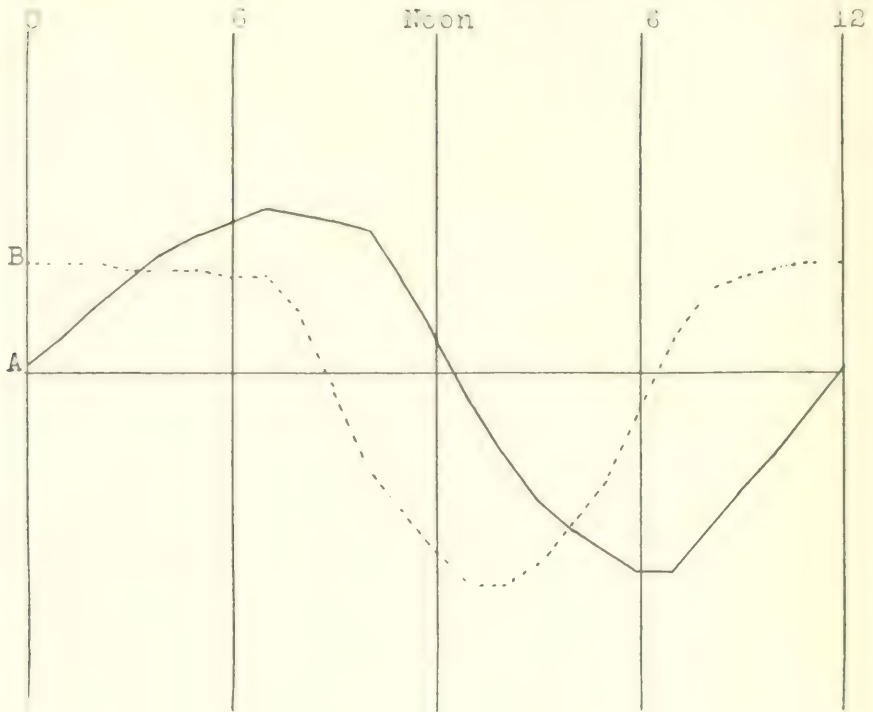


FIGURE 8.

Mean diurnal variations of north magnetic component at Palo Alto compared with the mean diurnal variation of earth potential.

Curve A indicates the magnetic variation and Curve B the earth potential variation with signs inverted.

It will be seen from the comparison of the two curves that the hypothesis of an increased magnetic field on the negative side of the earth is not substantiated, there being about five hours' difference between the maxima or the minima of the two curves. This would seem to indicate that the diurnal variation in the north magnetic component is not wholly, if at all, dependent upon the electric state of the earth in the vicinity of the magnetometer, but is more likely dependent largely upon variations in the west-east earth-current by which the equilibrium of the potential difference on the two sides of the earth is maintained.

#### Magnetic Declination

The diurnal variation in magnetic declination was determined for the months of September and October, 1922. The mean values of this

variation for the two months is shown below, expressed in millimeters variation on the record sheet.

TABLE VI.

| A. M.      | 1   | 2   | 3   | 4  | 5  | 6   | 7   | 8   | 9   | 10  | 11  | Noon |
|------------|-----|-----|-----|----|----|-----|-----|-----|-----|-----|-----|------|
| Sept. .... | -1  | +2  | +1  | +5 | +7 | +12 | +30 | +28 | +23 | +3  | -15 | -28  |
| Oct. ....  | +1  | +8  | +6  | -5 | -9 | +2  | +1  | +12 | +18 | +2  | -17 | -21  |
| Mean. .... | 0   | +5  | +3  | 0  | -1 | +7  | +15 | +20 | +20 | +2  | -16 | -24  |
| P. M.      | 1   | 2   | 3   | 4  | 5  | 6   | 7   | 8   | 9   | 10  | 11  | 12   |
| Sept. .... | -30 | -25 | -18 | -7 | +2 | +1  | -4  | +2  | +6  | +4  | +6  | -1   |
| Oct. ....  | -26 | -20 | -5  | 0  | +8 | +7  | +13 | +14 | +8  | +12 | +6  | -4   |
| Mean. .... | -28 | -22 | -11 | -3 | +5 | +4  | +4  | +8  | +7  | +8  | +6  | -2   |

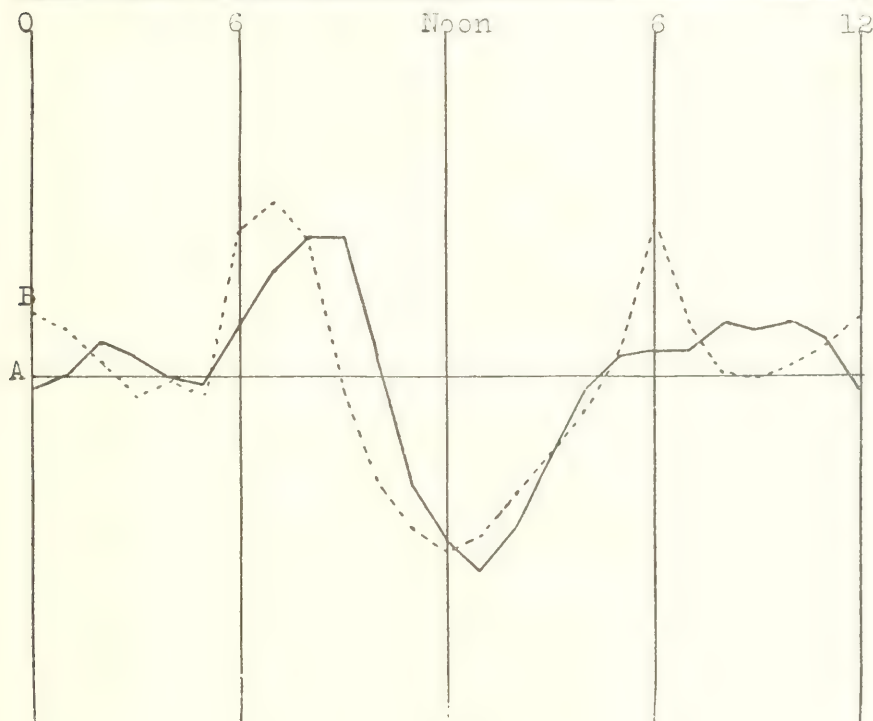


FIGURE 9.

Mean diurnal variation of magnetic declination compared with the mean diurnal variation of the N-S earth-current.

Curve A indicates the magnetic variation and Curve B, the earth-current variation.

In Figure 9 this variation is shown graphically in Curve A, while Curve B shows the diurnal variation of the N-S earth-current as given in Figure 6. In an article in *Science* of October 27, 1922, I have shown from Weinstein's data\* on the diurnal variation of earth-currents and magnetic declination, as well as from similar data in the bulletins of *Observatorio del Ebro*, that the variations in magnetic declination are in the direction that they would be if they were produced by the N-S earth-current, and that the rate of change of the magnetic declination for a given period is proportional to the strength of the N-S earth-current for that period.

### SOME THEORETICAL CONSIDERATIONS

#### The Magnitude of the Sun's Charge

In *Astrophysical Journal* 43, 347 (1916) and in *Contributions from Mt. Wilson Observatory*, No. 109, Carl Störmer undertakes to calculate the moving charge necessary to account for the magnetic field observed in the center of a sun spot. He decides that, "*The Zeeman effect is due to a whirl of negatively charged electrical particles.*" He then proceeds to calculate the magnitude of the electrical charge which must be in motion to produce a magnetic field of 3,000 gaussess over a central area 500 kilometers in radius. Depending upon St. John's observations of the speed of rotation observed in some of the sun spot vortices, he assumes that the charge which is concerned is carried around in a vortex whose outer radius is 50,000 kilometers, and whose speed at a distance of 11,250 kilometers from the axis is three kilometers per second. He estimates the depth of this vortex to be about 500 kilometers, and concludes that throughout the whole of the vortex the moving gases must carry a negative charge of .052 E.S.U. per cc. This would give a surface density of charge of  $2.6 \times 10^6$  E.S.U., or 780,000,000 volts over an area about fourteen times as great as the surface of the earth.

There is no known method by which such a charge could be localized upon a conductor except by the induction of a much greater charge on some other conductor, and yet the magnetic fields of sun spots usually persist for months.

If such a charge were produced by the separation of the positive and negative ions of the sun, there would be positive ions enough to charge the rest of the sun's surface to a potential of more than 3,600,000 volts. It seems to the present writer much more probable that the whole surface of the sun is charged to the same potential as the vortex region around the

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\* *Die Erdströme im Deutschen Reichstelegraphengebiet*, Braunschweig, 1900.

sun spot than that a charge of so great a magnitude has been isolated there in contradiction to all the known laws of electrostatics.

But even the charge which would result from Störmer's computation is probably too small to account by its rotation for the magnetic field of the sun. Rowland\* has computed that the charge which would be required to produce by its rotation the magnetic field of the earth would be sufficient to charge the earth to a negative potential of  $41 \times 10^{15}$  volts. Rowland then says:

Such an electrostatic force as this would undoubtedly tear the earth to pieces, and distribute its fragments to the uttermost parts of the universe. If the moon were electrified to a like potential, the force of repulsion would be greater than the gravitation attraction of the earth, and it would fly off through space.

For these reasons I rejected the theory, and now believe that the magnetism of the earth still remains, as before, one of the great mysteries of the universe, toward the solution of which we have not yet made the most distant approach.

Many other physicists have thought it necessary to reject the possibility of a charge of such magnitude for the same reasons. Their arguments seem to be based upon the belief that an electrostatic charge is held to a conductor by its attraction for the atoms of the conductor, though it has been plain ever since the capacity of a conductor was shown to depend upon its surface, and not upon its mass, that there can be no attraction between the atoms of a conductor and the particles of the electric fluid. It follows as a matter of course that no repulsion between the electric particles on a conductor would tend to separate its atoms.

Lindemann† takes a still more indefensible view of the situation and claims that the sun can have no electric charge greater than could be held to its surface by the gravitation force on its ions. From this point of view he calculates the maximum possible potential of the sun's charge as 1,980 volts. This assumption would seem to make it impossible to charge any conductor on the earth, since the earth's gravitation attraction would be many times that of the conductor. It would also make impossible the enormous charges which are known to be in revolution about sun spots.

Regardless of the many guesses that have been made as to how an electric charge is retained upon a conductor, it is a well-known fact that clouds may be charged to a potential of millions (perhaps thousands of millions) of volts without their particles being dissipated by the repulsion of the charges which they carry. In fact, it is usually taught that these tremendous charges are built up by the coalescing of many smaller charged particles into larger ones.

It is probably true that charges upon the planets and sun of the

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\* *Phil. Mag.*, VIII, 102-106 (1879). *Coll. Papers*, p. 182.

† *Phil. Mag.*, 38, 669 (Dec., 1919).

magnitude required by Rowland's calculation would make necessary a revision of our estimates of the masses of some of the planets, and it is also possible that they would have to be taken into consideration in explaining the perturbations of some of them, as Mercury or the moon; but even in that case they would be no worse than relativity.

On the other hand, Sutherland\* has computed the density of the charge over the earth which would be required to produce its magnetic field by its rotation as 51,000 E.S.U., or  $17 \times 10^7$  volts (this seems to involve an arithmetical error). This would make Rowland's estimate about three-thousand-million times as great as Sutherland's, which leaves a wide range for other computations.

Franz Exner† has calculated the negative electrical potential of the earth on the basis of Erman's theory that the atmospheric potential gradient is merely a manifestation of the induction of the earth's charge. One of his results makes the potential of the earth  $-4 \times 10^9$  volts.

Whatever may be the negative potential of the earth, that of the sun must apparently be much greater. According to Rowland's computation, the magnetic force inside a charged, rotating sphere is given by the equation  $F = \frac{2}{3} \omega V$ , where  $V$  is the electric potential of the sphere,  $\omega$ , its

$n$

angular velocity and  $n$  the ratio of the electromagnetic to the electrostatic unit of electricity. Since  $n$  is a constant,  $F \propto \omega V$ , regardless of the dimensions of the sphere.

Since the magnetic field of the sun has about fifty times the intensity of that of the earth while its angular velocity is about  $\frac{1}{27}$  that of the earth, the negative potential of the sun should be about 1,350 times that of the earth, and since its electrostatic capacity is 100 times that of the earth, its negative charge should be about 135,000 times that of the earth.

The electrical charges of the sun and moon may be compared by their efficiency in producing the diurnal variations in electrical potential at a given place upon the earth. Thus, these electrical tides may be compared with the gravitational tides, since both the gravitational and electrical forces follow the inverse square law. The electrical tidal effect should accordingly vary with the charge of the inducing body and inversely as the cube of its distance, i. e., as  $Q/d^3$ .

If two bodies whose tidal effects are to be compared are at the same electrical potential, their charges are proportional to their respective radii, and their electric tidal effects upon a distant body should be proportional to  $R/d^3$ .

\* *Terr. Mag.*, 8, 51 (1900).

† *Rep. d. Phys.*, XXII, 479.

The distance of the sun from the earth is approximately 400 times that of the moon, and the radius of the sun is 402 times that of the moon. If the two bodies are at the same electrical potential, the electrostatic tides upon the earth due to the moon should be  $400^3/402$ , or 160,000 times as great as those due to the sun. The lunar electric tides seem from data thus far acquired to be of the order of one-tenth those of the sun, hence the sun's negative potential would seem to be of the order of 1,600,000 times that of the moon.

We have seen that when computed from their magnetic fields the electric potential of the sun is about 1,350 times that of the earth, hence the negative potential of the moon would seem to be about  $\frac{1}{1200}$  that of the earth.

If, as the tidal theory of the moon's origin assumes, the moon was once a part of the earth, it would seem that it must have broken away while on the electropositive, *i. e.*, the day side of the earth.

#### **On the Displacement of the North Magnetic Pole of the Earth From the North Geographical Pole**

If, as has been here supposed, the principal magnetic field of the earth is due to the carrying around of its negative charge by the rotation of the earth, and if the earth were of uniform magnetic permeability, the primary magnetic axis of the earth would coincide with its rotational axis.

If the sun by its electrostatic induction maintains an excessive negative charge on the night side of the earth and a deficiency of negative charge on the day side, there must be continuous streams of electrons moving ahead of the sun from the day side to the night side of the earth; or in the conventional language of currents, there must be continuous electric currents flowing from west to east around the earth. The effect of these induced currents is to weaken the primary magnetic field of the earth.

If the surface conductivity of the earth were everywhere the same, this great current, while subject to seasonal changes in direction, would still, in general, flow from west to east, and would have no tendency to produce a change in the position of the earth's magnetic axis, but only a decrease in the intensity of the earth's magnetic field.

But the water of the oceans is a much better electrical conductor than are the solid materials of the earth, hence we should expect these induced currents to take a water route instead of a land route wherever possible.

The most nearly continuous east and west water route around the earth passes about ten degrees north of the Equator on the American side and about an equal distance south of the Equator on the Asiatic side. Currents flowing from west to east around this route would induce a

magnetic field with its axis inclined about ten degrees from the rotational axis of the earth and with its northerly magnetic pole on the Asiatic side of the geographical pole. Since this magnetic pole would be opposite in character to the north magnetic pole of the earth's primary magnetic field, the resultant north magnetic pole of the earth would be displaced toward the American side by an amount depending upon the relative intensity of the two magnetic fields.

Such west-east earth-currents are observed everywhere upon the earth, and their preference for water routes has been observed. Their resultant effect must be to set up a magnetic field perpendicular to the plane of their mean path which will be opposite in character to the principal magnetic field of the earth.

### Future Work

No discussion of the numerous problems in electrostatics as well as in cosmical physics which are suggested by these observations will be attempted in this bulletin. The purpose of its publication is principally to announce to other workers in Terrestrial Electricity and Magnetism a new line of observation which seems to serve as a connecting link between numerous phenomena which are known to have a physical relation to each other, but which do not seem in general to be related as cause and effect. I shall be very glad if other observers will install electrometers for measuring the potential variations of the earth in their localities.

Through the generosity of Professor Jeremiah W. Jenks, of New York City, I have been able to erect a small observatory in Palo Alto, where records of earth potential variation and earth currents are being continued, and where an electrometer has been installed for simultaneous records of air potential variation. These seem especially important, since the observations here published seem to substantiate Erman's theory that the atmospheric potential gradient is an induction phenomenon due to a highly electrified earth. To keep the variations of potential in the earth and the air separate, I am measuring the variation between two points in the air, one of which is two meters higher than the other.

I do not wish to close this report without acknowledging my obligations to Mr. Burton Stuart, of Stanford University, without whose assistance in the preparation of apparatus this investigation would have been greatly hampered.

FERNANDO SANFORD.

